National Aeronautics and Space Administration

Microwave Frequency SQUID Multiplexer

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Project Objective:

We are developing a readout multiplexer for arrays superconducting bolometric detectors, particularly transition edge sensors (TES), which are a leading candidate detector technology for many next generation astronomical instruments. Our objective is to extend the microwave frequency domain multiplexing technique developed for Microwave Kinetic Inductance Detector (MKID) arrays to TES, and hence to increase the multiplexing factor (number of detectors per readout channel) of current TES array readouts to 10^3-10^4. To accomplish this, we have developed a SQUID amplifier which is coupled to a lithographed superconducting micro-resonator. The output of this combined device (the MSQUID) is interrogated with a microwave frequency signal. We have demonstrated this technique by constructing and measuring a small array of 16 MSQUIDs.

Principles and Techniques:

- Each SQUID is part of a resonant circuit with a unique resonant frequency.
- A single microwave readout line connects to an array of MSQUIDs
- A comb of microwave frequencies is used to simultaneously excite all of the resonant circuits of the array.
- The frequency and quality factor, Q of the resonance varies as the flux state of the SQUID changes.

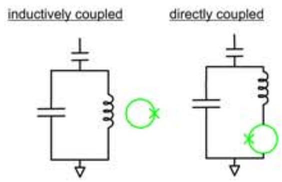


FIGURE 1. Schematic the microwave SQUID circuit (single device) illustrating coupling of the microwave resonant circuit to the SQUID loop.

FY09 Results:

16-element arrays

- The prototype device (fig. 2) has 16 MSQUIDs, each with a 300nH input coil for coupling to the signal from a TES.
- A single coplanar strips (CPS) transmission line is for the microwave excitation/ output signals.
- The resonant frequencies are around 3.5GHz, and Q ~ 1000 (fig. 3).
- The microwave tone corresponding to a particular resonator is tuned to its resonance frequency. As the flux state of the SQUID changes, the changing resonator frequency and Q modulates the readout tone.

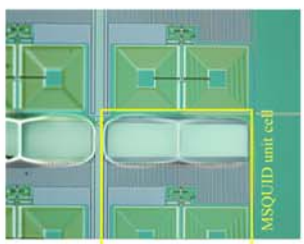


FIGURE 2. 16-element Prototype device, the size of the unit cell is 0.5x0.5mm.

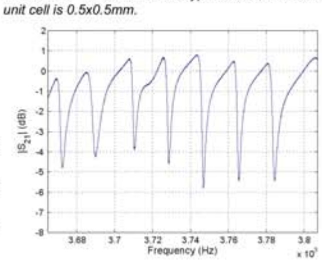


FIGURE 3. Transmission through the array measured at 4.2K.

Modulation Technique

- Typically SQUID readout electronics employ feedback to keep the flux in the SQUID loop at a sensitive part of the modulation function and to linearize the output.
- Separate feedback lines for each SQUID of a large array would be impractical, so we choose to operate in an open loop mode.
- To avoid individual flux biasing, we apply flux modulation to all of the SQUIDs using a common modulation line.
- The output of each SQUID is lock-in detected both at f and $2f$, giving outputs I and Q, where

$$I(\Phi) = \langle \sin\omega t \cdot S(\Phi + A\sin\omega t)\rangle,$$

$$Q(\Phi) = \langle \cos 2\omega t \cdot S(\Phi + A\sin\omega t)\rangle,$$

and < > indicates time average. A is the amplitude of the flux modulation, w is the angular frequency and S is the SQUID modulation function. F represents the external magnetic flux.

- A phase angle can be defined by

$$\theta(\Phi) = \tan^{-1}\left(\frac{Q(\Phi)/Q_m}{I(\Phi)/I_m}\right),$$

where Im and Qm are the maximum values of I and Q. Q is a (close to) linear representation of the SQUID signal and phase-wraps for large signals.

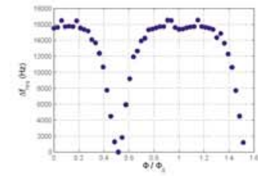


FIGURE 4. (Top) Response of an inductively coupled MSQUID resonance to input flux. The peak-to-peak frequency modulation is 16kHz.

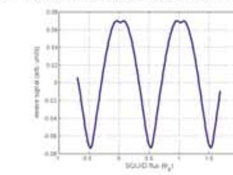


FIGURE 5. Response of a fixed frequency microwave excitation signal to input flux.

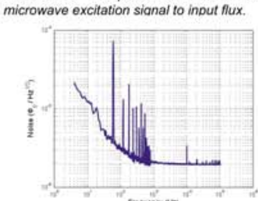
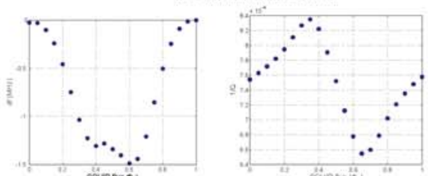


FIGURE 6. Measured noise of $2mF_0$ / $Hz^{1/2}$ (above the 1/f knee), corresponding to an input current noise of ~ $2\mu A$ / $Hz^{1/2}$, much lower than the current noise of a TES.

Figure 7. Modulation of resonance frequency and Q for a directly coupled MSQUID. Peak-to-peak frequency shift is 1.5 MHz. Extra credit: explain the shape of the 1/Q modulation curve.



Benefits to NASA and JPL:

- Submillimeter/ FIR astronomy: Once the detectors an array have reached background limited performance, where noise is limited by the random arrival times of the detected photons, the only way to improve the sensitivity of an instrument is to increase the number of detectors. Next-generation astronomical instruments for the Sub-millimeter and Far-Infrared bands will require pixels counts of 10^4 – 10^6, yet current state-of-the-art TES readouts have a multiplexing factor of at most 32.
- X-ray astronomy: The resolution of x-ray microcalorimeters is inversely related to their size, so the pixels must be kept small and pixel counts of 10^4-10^5 will be needed to collect the x-ray flux from a next-generation space telescope.
- By providing a much greater multiplexing factor, MSQUID arrays provide a solution instrumenting several planned astronomical missions including SAFIR, SOFIA and IXO.
- The CCAT ground based observatory will require very large arrays in the Submm/FIR and would be a testbed for this technology.

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